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GLACIAL LANDFORMS AND WEATHERING PROCESSES IN THE BALCHENFJELLA REGION, EASTERN PART OF THE SØR RONDANE MOUNTAINS, EAST ANTARCTICA

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Abstract: Glacial landforms and weathering processes have been investigated in the Balchenfjella region, eastern part of the Sør Rondane Mountains, East Antarctica. This region had entirely been covered with the former ice sheet, and shows less alpine features in comparison with the other parts of the Sør Rondane. Deglaciation occurred at first in the northern region, Vesthjelmen-Austharmaren area. Succeedingly, the southern part of South Balchenfjella and the mountain tops in the Bulken-Hesteskoen area became free from ice. North Balchenfjella emerged in the latest stage of deglaciation. Around the areas from Bulken to South Balchenfjella, different stage of deglaciation was probably due to the ice step which had been formed by damming of ice flow by the mountain's threshold. The step still remains behind the South Balchenfjella area.

Shattering and granular disintegration are most predominant among weathering features in this region. Salt aggregations, mostly gypsum, are observed in any locality. Beautifully crystallized gypsum was predominantly found in the North Balchenfjella area. Desert varnish was also examined. Chemical analysis clearly defined that the desert varnish is a film composed of crystalline jarosite mixed with amorphous silica. The varnish coat is formed by a solution of sulfuric acid from the underlying ground. Capirally action is effective for this solution to ascend through very narrow cracks within a rock.

1. Introduction

The Sør Rondane Mountains is located about 200 km south of the coast of Breid Bay, East Antarctica. Ice-free mountain ranges intermittently extend about 250 km long from west to east. Preliminary studies of geomorphology and glacio-geology of the Sør Rondane Mountains have been performed by the Belgian expeditions (VAN AUTENBOER, 1964; VAN AUTENBOER and BLAIKLOCK, 1966). Geomorphological and geological investegations have also been conducted in the western and central parts of the Sør Rondane by the summer teams of the 25th to 28th Japanese Antarctic Research Expeditions (JARE-25 to 28) from 1984 to 1987. A detailed study of slope development of the western part of the mountains was conducted by IWATA (1987), and a history of glaciation of the central part was studied by HIRAKAWA *et al.* (1988). Nevertheless, landforms have not yet sufficiently been studied in the

"Balchenfjella region", eastern part of the Sør Rondane. One of the authors was given an opportunity to carry out the geomorphological survey in the Balchenfjella region during the summer field investigations of JARE-29 (January 1988). The purpose of this paper is to note the glacial landforms and weathering processes observed in the Balchenfjella region with special reference to salt aggregation and the origin of desert varnish.

2. Description of Glacial Landforms and Weathering Phenomena

The Balchenfjella region occupies the easternmost part of the Sør Rondane Mountains. A large outlet glacier named Byrdbreen separates it from the central part of the Sør Rondane. Glaciated ridges and the presence of erratics indicate that the former ice sheet has covered most of the Balchenfjella region. Peaks in this

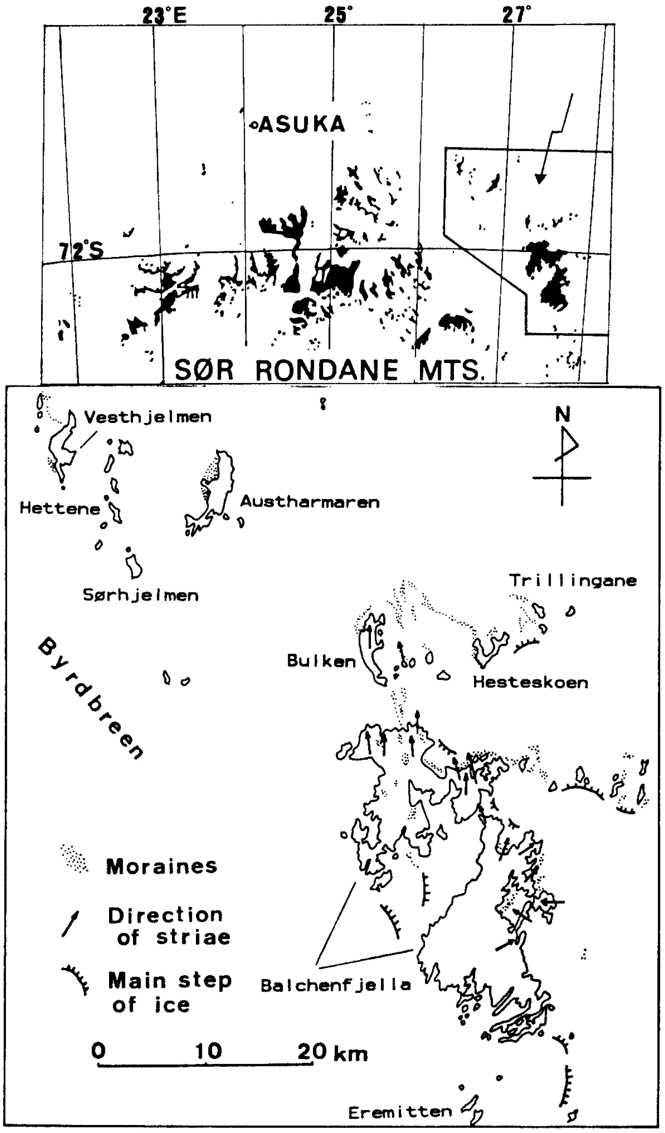

Fig. 1. Map of the Balchenfjella region.

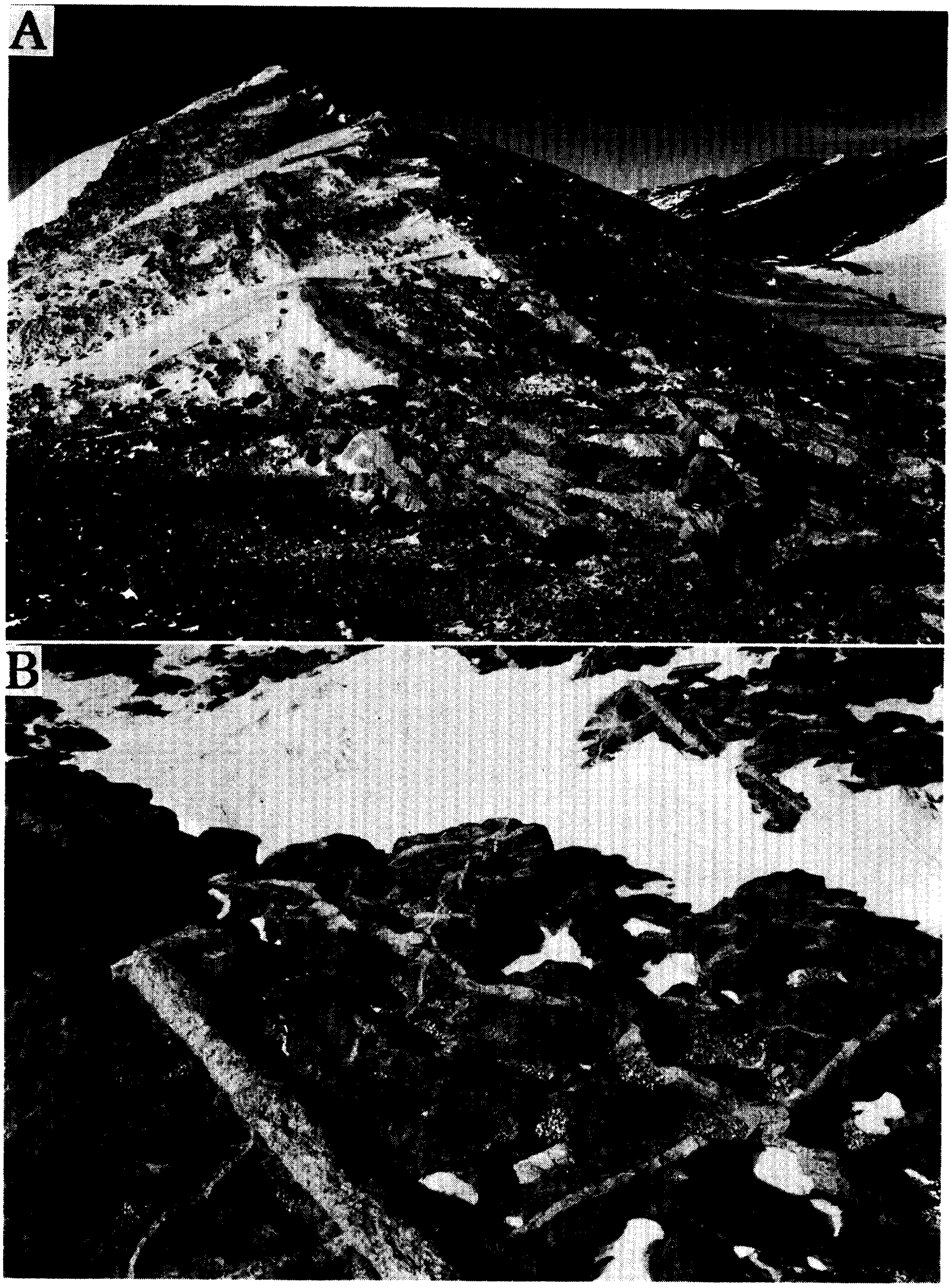

Plate 1. *A: Marble veins on the ridge of Austharmaren. White-colored marble veins stand about 50 cm higher than the surrounding bedrock.*
B: A typically honeycomb-weathered bedrock to the north of Søhrhjelmen. Attention to less weathered granite veins.

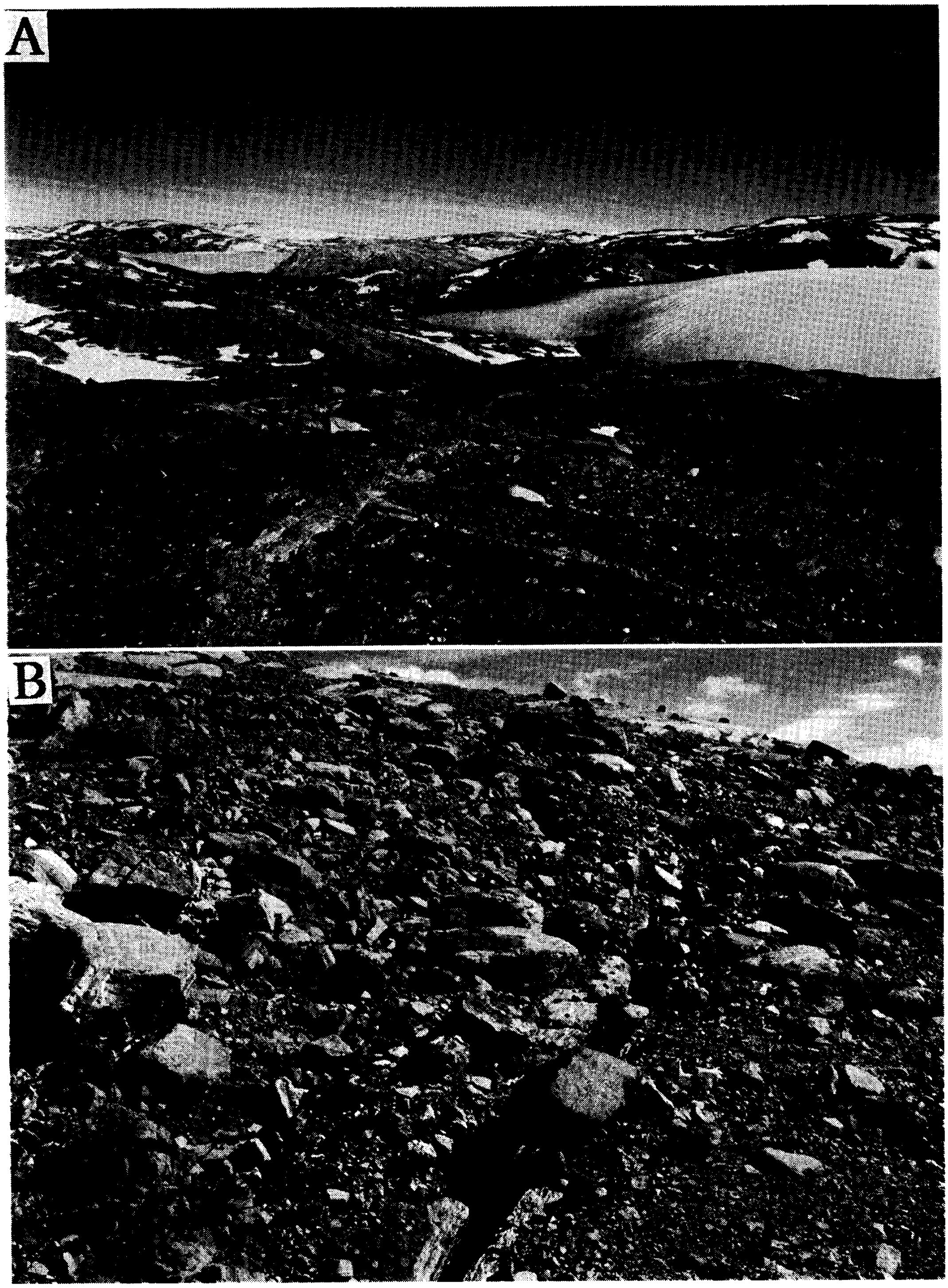

Plate 2. A: North Balchenfjella, viewed from the western part. South Balchenfjella stands behind leftside.
B: A joint-block split on the mountain top in the central part of North Balchenfjella. Gneiss bedrock has been riven 15 cm wide along the foliation.

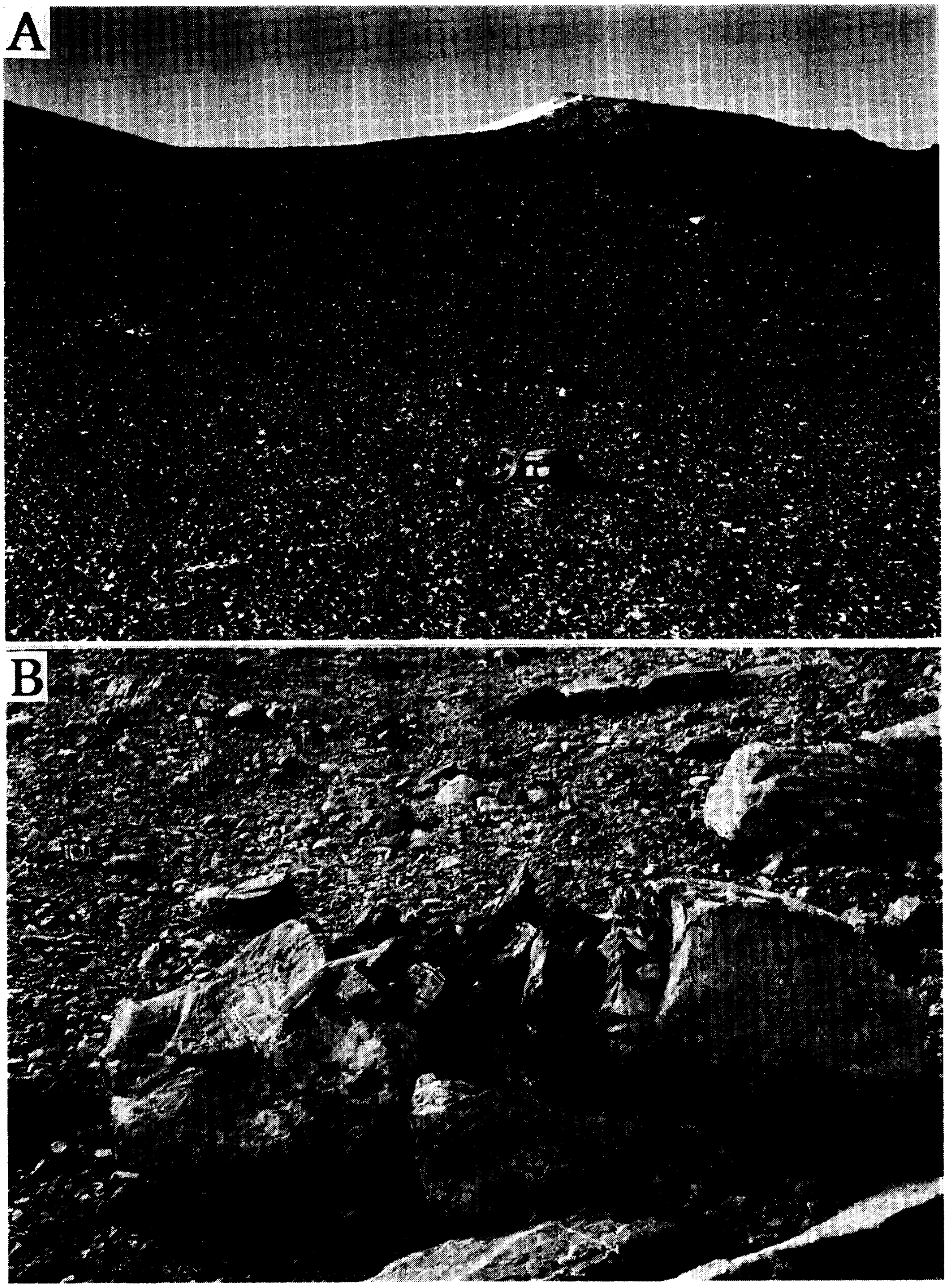

Plate 3. A: Desert pavement at the end of the southwestern part of South Balchenfjella. Blocks of boulder size are rarely found.
B: A shattered and disintegrated gneiss boulder in the central part of North Balchenfjella.

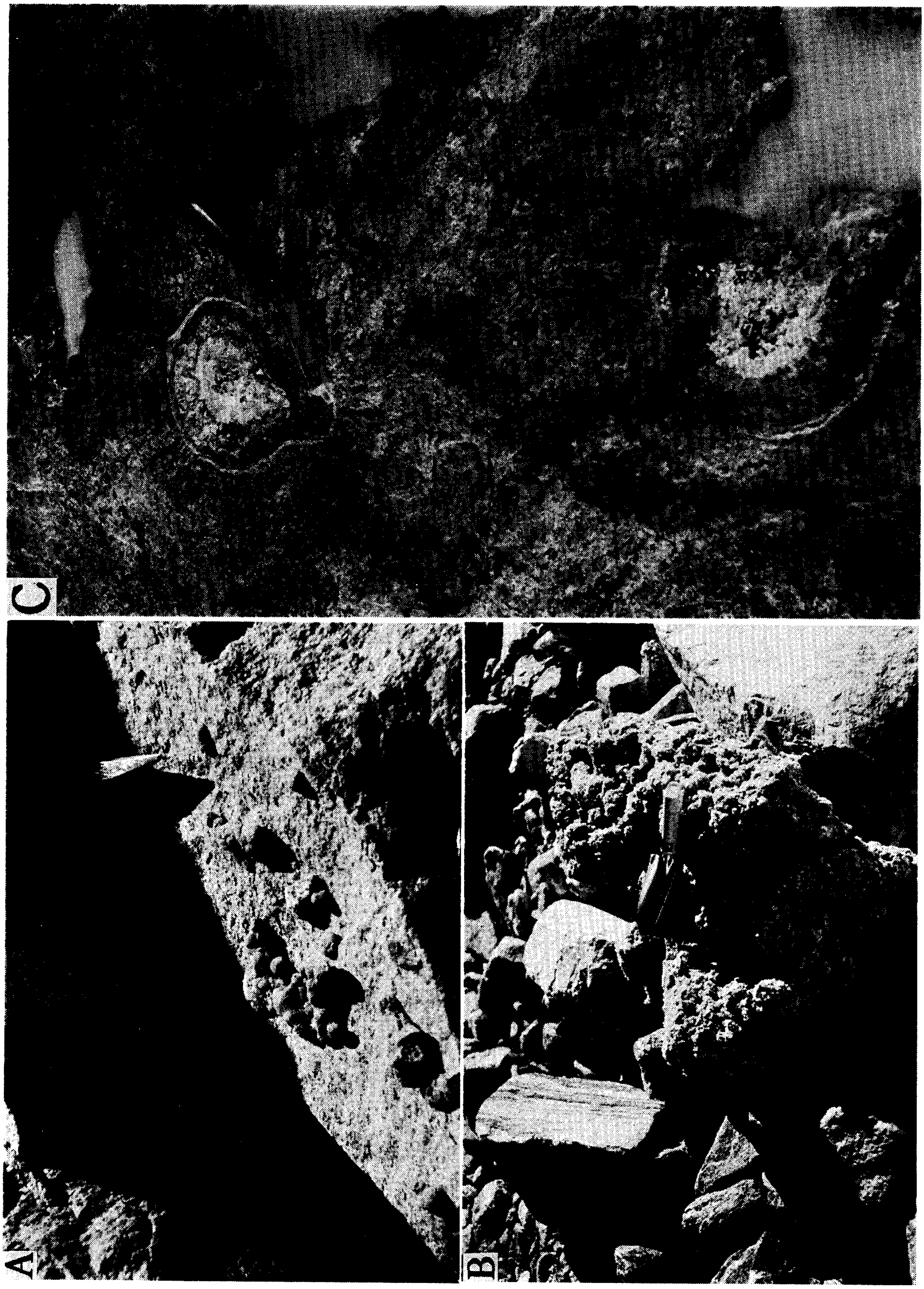

Plate 4. A: Greyish gypsum aggregates like bird's droppings in the central part of South Balchenfjella.
B: A gypsum lump like horse's dung on the morainic hill at Austharmaren.
C: Ring-like incrustations of gypsum in the central part of South Balchenfjella.

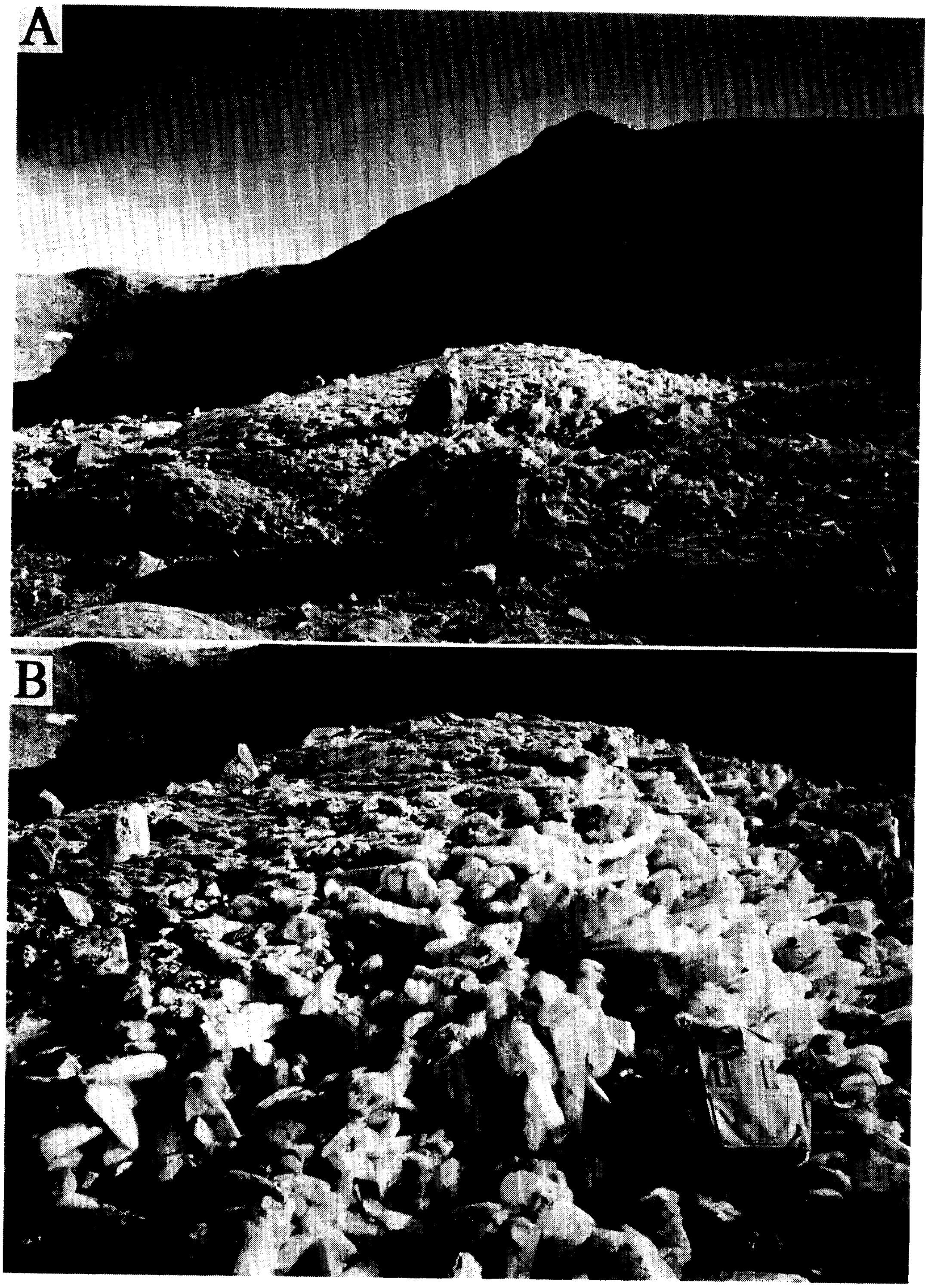

Plate 5. A: The bottom of a deep depression in the central part of North Balchenfjella. A whitish mound is covered with gypsum crystals.
B: Beautifully crystallized gypsum, a close-up view of 5.A.

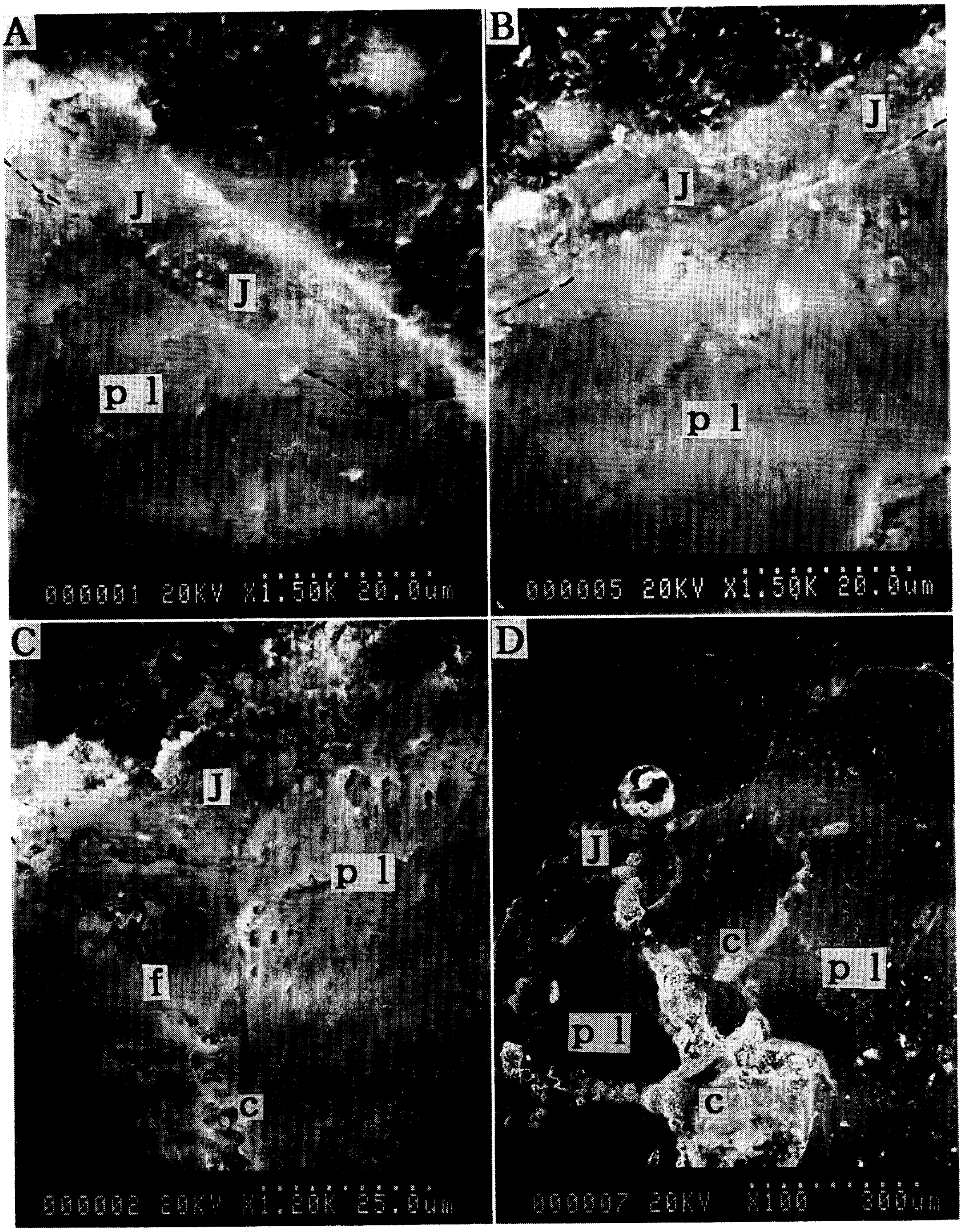

Plate 6. A: Microphotograph of desert varnish. A film of crystalline jarosite mixed with amorphous silica covers the surface of a rock.
B: Ibid.
C: A varnish coat of crystalline jarosite mixed with amorphous silica and a crack filled with jarosite. D: Ibid. Part of varnish coating is missing.
J: crystalline jarosite mixed with amorphous silica, pl: plagioclase, f: potash-feldspar and c: crack filled with jarosite. Dotted line shows a boundary between the varnish coat and the surface of a rock.

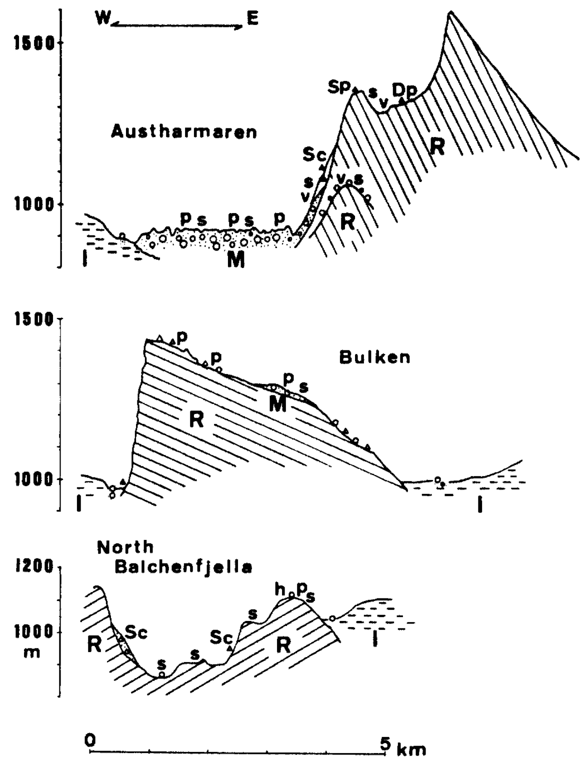

Fig. 2. Schematic profiles of landform with weathering phenomena; Austharmaren, Bulken and North Balchenfjella. R: Bedrock, I: Glacier, M: Moraine or till, Sc: Scree, Sp: Stone pavement, Dp: Desert pavement, P: Patterned ground, S: Aggregated salt, h: Honeycomb weathering and V: Desert varnish.

region never exceed 2000 m above sea level (hereafter a.s.l.) and are rather lower than those in the other parts of the Sør Rondane. The Balchenfjella region can be subdivided into four parts from north to south in terms of topography: Austharmaren-Vesthjelmen, Bulken-Hesteskoen, North Balchenfjella and South Balchenfjella areas. Map of the studied area is shown in Fig. 1 and schematic cross profiles of landforms with weathering phenomena are drawn in Fig. 2.

2.1. *Austharmaren-Vesthjelmen area*

In the Austharmaren-Vesthjelmen area, remarkable sharp ridges stretch in the north-south direction and are exposed 500 to 800 m high above the ice. These ridges show asymmetric features. Rather gentle and rough slopes covered with veneers of erratics and/or weathered lag deposits are facing to the east. On the other hand, steep cliffs which have been truncated by glaciers rise higher than 300 m on the western face. Banks of lateral moraines appear along the feet of cliffs. Field surveys were carried out mainly at the eastern slopes in Vesthjelmen up to 1200 m a.s.l., ridges up to 1400 m a.s.l. and widespread banks of lateral moraines in Austharmaren, and lateral moraines in Hettene. So far as the authors investigated, erratics were found in every locality. It means that the ice sheet has once covered the Austharmaren-Vesthjelmen area during the former glaciation.

In Austharmaren, outcrops of gneiss are strongly shattered around the mountain tops, and stone pavements are sometimes found. They are composed of angular to sub-angular and flat fragments probably due to frost weathering. Massive marble veins were observed to remain at highest 50 cm above the surrounding gneiss bedrock (Plate 1.A).

The eastern mountainside of Vesthjelmen is almost entirely covered with lag deposits, and solifluction lobes several meters wide, 2 to 3 m long and 0.5 to 1 m high are predominantly developed. On the lateral moraines of Austharmaren and Hettene, which were confirmed to be ice-cored, slightly sorted polygons less than 2 m in diameter and heaps like hummocks are frequently distributed. Small patches of aggregated salt are recognized on the surfaces of erratics.

Honeycomb or cavernous weathering sometimes occurs on rock walls and huge erratics in this area. An outcrop with well-developed honeycomb-weathered hollows is found in a small ice-free area to the north of Sørhjelmen which is rather low in elevation and seems to have been deglaciated in recent years. Maximum size of cavernous hollow is 30 cm in diameter and 30 cm in depth. Hollows are sometimes full of fragments and coarse grains derived from adjacent bedrock. Formation of cavernous hollows is considered to be controlled strongly by lithology, because they develop on the hornblend-bearing biotite gneiss bedrock and are rarely found on the surface of granite veins (Plate 1.B).

2.2. Bulken-Hesteskoen area

The summit level of the mountain is about 1400 to 1470 m a.s.l. and asymmetric ridges can be seen in the Bulken-Hesteskoen area. Gently inclined surfaces near the summits are abruptly broken by vertical cliffs truncated from the west.

There exists a small step at about 1300 m a.s.l. on the eastern slope of Bulken. A rather fresh outcrop with glacial striae is observed on that step. Below the step, the ground surface is covered with thin deposits of till where salt crystals sometimes occur. Around the summit above the step, weathered lag materials are predominantly distributed on the surface, and small heaps like hummocks and hillocks like tors are recognized. Ridges above the step are considered to have been freed from ice during an earlier stage than those below the step. The difference between the upper and lower parts can clearly be distinguished by color in aerial photographs; the former is dark brown and the latter light grey.

In Hesteskoen, the mountain top is extremely flat and erratic boulders probe it to be glacial in origin. Small hollows like pot holes, 30 cm wide and 20 cm deep in maximum size, are recognized on the southern mountainside. They are mostly filled up with foreign gravels. A small local cirque glacier, which is rarely found in the other parts of the Balchenfjella region, is seen to the northeast of Hesteskoen.

Desert pavement extensively develops on an isolated ice-free mountain south of Trillingane, where southerly to southeasterly wind was blowing too violently to let one stand still without any props during the summer field survey. A thin layer of angular and sub-angular gravels of pebble size spreads on the ground surface and is overlying the yellowish fine materials 10 to 15 cm thick, mainly composed of sand mixed with silt.

2.3. North Balchenfjella area

Most conspicuous stoss-and-lee topography appears in North Balchenfjella. An arrangement of smoothed and rounded summits gives an appearance like a giant roche moutonnée. Mountain summits usually display bare bedrock surface bearing glacial striae. Several deep basins are also strikingly developed in this area. These basins are elongated in the north-south direction and look like spoon-scooped depressions. No glaciers are existing in these basins and morainic deposits are rather poor on the bottoms. However, they are a kind of glacial trough because of glacial striae observed on the bedrock surface at the bottom.

The height of the summit level is about 1000 to 1300 m and the bottom of a depression 800 to 900 m a.s.l. As a surrounding ice level is about 1000 to 1200 m a.s.l., most of the ice-free areas in North Balchenfjella are situated below the level of the present ice (Plate 2.A). The surface of the outcrop is quite fresh in comparison with that of the other parts of the Balchenfjella region.

Aggregations of secondary salt crystals are commonly observed in this area. Single crystals of gypsum are often scattered around the depression and the adjacent area. Small polygons and contraction cracks are recognized on the ground covered with thin morainic or lag deposits. An extraordinary joint-block split is found on the rounded top of mountain where an opening 20 m long, 15 cm wide and 50 cm deep was produced along the foliation of gneiss bedrock (Plate 2.B).

On the other hand, only the eastern part of North Balchenfjella has the topography different from the central and western parts. Low ridges and shallow valleys covered with a thin mantle of weathered lag are seen. These features are similar to those of the South Balchenfjella as will be mentioned below.

2.4. *South Balchenfjella area*

The ice-free area of South Balchenfjella is the widest in the Balchenfjella region. The summit level of this area gently inclines from south to north and the highest point is about 1900 m a.s.l. in the southernmost part. The northern part of South Balchenfjella is mostly below the present ice level and glaciated trough walls exist as in North Balchenfjella.

In the central and the southern parts of this area, several lines of small ridges and valleys stretch in the NE-SW direction. This direction may be accounted for the foliation of gneiss and the joint system. The bedrock surface is often covered with veneers of moraine and/or lag materials and is characterized by hillocks and small depressions. No definite morainic hills are found except those of marginal zones on the present ice sheet. In the southwestern part of this area, short knife ridges abruptly appear. Almost vertical walls stand higher than 100 m on ridges stretching from the central part. Desert pavement develops on the lower gentle slopes at the end of the southwestern part (Plate 3.A). Salt crystals occur mainly from the central to the northern parts of South Balchenfjella.

2.5. *Degree of weathering in the Balchenfjella region*

In the Balchenfjella region, physical weathering is most predominantly observed. Shattering and granular disintegration of bedrock and erratics have been recognized more or less in any locality (Plate 3.B), though their effect depends upon a stage of deglaciation, local climatic condition, and physical properties of exposed material. Frost weathering is considered to be an important process in this region, where drifting snow has often been observed and melt water occurs during the summer season.

Salt weathering is probably another important process because of frequently appearing salt aggregation as will be mentioned later.

Based on the field investigation around the ice-free summits, the following inference can be drawn in respect of the degree of weathering in this region. Ridges of Austharmaren-Vesthjelmen area show the most advanced stage of weathering in the Balchenfjella region, where the surface appears very rough, never polished and rounded. There sometimes occurs stone pavement or desert pavement composed of shattered rock fragments without any size of boulders. Degree of weathering shows the second advanced phase in the southern part of South Balchenfjella and on the summits of the Bulken-Hesteskoen area. There, an uneven surface develops and is covered with a mantle of weathered lag. A similar coarse surface with lag materials is also observed in the central part of South Balchenfjella to the eastern part of North Balchenfjella. But in these areas it remains still roundish and glacial striae are sometimes distinguishable. Weathered features seem poorest in North Balchenfjella, where polished and smoothly rounded surfaces extensively remain.

As ice-free areas of the Balchenfjella region are mainly composed of gneiss bedrock, lithological differences may not be a causative factor of weathering on a large scale. Spatial variation in the degree of weathering around the summits can be explained in terms of the stage of deglaciation. That is to say, the more intensively weathered ridge became free from ice cover in the earlier stage. However, weathering is less advanced on the lower ridges or at the mountain foot in each area.

3. Deglaciation of the Balchenfjella Region

Glacial striae and glaciated valleys indicate that the past glacier flowed generally from south to north as shown in Fig. 1. This direction is roughly the same as that of the present main outlet glaciers which cross over the Sør Rondane Mountains. It means that this region has entirely been covered with the ice sheet flowing northward during the maximum glaciation. The ice sheet has perhaps continued to retreat since the deglaciation had started. No definite facts were found to indicate that the deglaciation was intercalated with a stage of positive glaciation. In this paper, the term stage is used in a relative sense because the authors were unable to get information on absolute age.

According to the degree of weathering as mentioned previously, deglaciation probably occurred first in the ridges of the Austharmaren-Vesthjelmen area. Then it took place in the southern part of South Balchenfjella and on the mountain tops in the Bulken-Hesteskoen area. After that, the central part of South Balchenfjella to the eastern part of North Balchenfjella became free from ice. At the latest stage, the ridges of North Balchenfjella entirely emerged from ice.

Figure 3 shows a schematic profile of the heights of ice-free areas and the present ice level from south to north. Around the Austharmaren area, the present ice level is almost equivalent to that of Byrdbreen, and it is estimated that the former ice surface was at least 300 to 400 m higher than the present. A notable ice step or fall is located around the southern part of South Balchenfjella, where the ice surface abruptly changes its level from 400 to 300 m in relative height. This step seems to have been

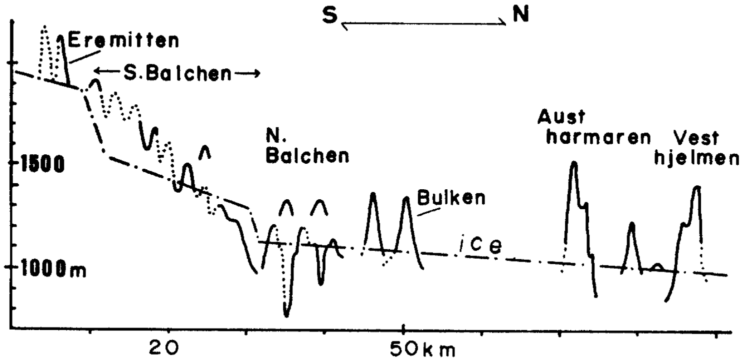

Fig. 3. A schematic profile of the heights of mountain tops and the present ice level in the Balchenfjella region. The profile is drawn approximately from south to north, between Eremitten and Vesthjelmen. Dotted line show supposed elevations of ice-free area.

formed by damming of ice flow by the mountain's threshold. The ice level behind South Balchenfjella was raised higher than the surrounding ice sheet. This ice rising is recognized to continue further southward, to Bleikskoltane. This ice step probably occurred in a rather earlier stage of deglaciation. It is certain that the ice rising and the step strongly controlled the local ice levels around the areas from Bulken to South Balchenfjella. Another small ice step is found on the ice sheet to the east of North Balchenfjella. A similar ice step or fall formed by damming has already been observed in the central part (HIRAKAWA *et al.*, 1988) and in the western part of the Sør Rondane Mountains (SOUCHEZ, 1966). Further research should be necessary to clarify the influence of this ice rising.

4. Salt Formation in the Balchenfjella Region

Secondary salt is observed in any locality of the Balchenfjella region. Salt incrustation and aggregation take various forms from spot to spot; band-like and ring-like coats, flower-like crystal, mushroom-like lump and so on. Some of them are shown in Plates 4.A to 4.C. An X-ray diffraction analysis proved that the salt consists mostly of gypsum.

The most striking feature among gypsum crystals is observed on the bottom of a deep depression in the central part of North Balchenfjella. Beautifully crystallized gypsum continuously covers the outcrops in this place, and forms a small knoll extending 1 m in height and 10 m in width (Plates 5.A, B). The maximum size of individual crystals is 30 cm in length, 5 cm in width and 3 cm in thickness. Similar assemblages of gypsum crystals are distributed in other places of North Balchenfjella.

The salt seems to have been crystallized from the residues of sublimated ice and to have been growing up during long period of time since deglaciation. Gypsum formation is probably influenced by sulfuric acid which is believed to be more concentrated on the ice of the inland area than of the coastal area in Antarctica. Gypsum crystals and other salt cumulation are more frequently observed at low positions rather than at the mountain tops. This means that somewhat hummid condition favored of salt growing in Antarctica where it is very arid. Adequate and intermittent water supply such as melt water and/or water vapor in the air seems to be necessary in proceeding salt crystallization.

Frequency of salt aggregation suggests that salt weathering is probably working in this region. In fact, whitish gypsum aggregation often occurs in contact with granular-disintegrated surface of bedrock or erratic, and sometimes in the hollows like tafonis.

5. Chemical Characteristics of Desert Varnish

At first sight, desert varnish is not necessarily well-developed in the Balchenfjella region. But the thin yellowish coats of desert varnish were sometimes distinguished on rock surfaces by detailed observation. In case of erratics, a coat of varnish usually covers the lee-side surface, whereas a wind-facetted dull surface appears on the windward in the Balchenfjella region, where southerly to southeasterly wind is prevailing.

Chemical characteristics of desert varnish have already been analyzed by many authors. ENGEL and SHARP (1958) distinguished a dark coating of desert varnish from underlying weathered rind and revealed by spectrographic analysis that H_2O, Fe_2O_3, and especially MnO showed the greatest enrichment in the varnish. HOOKE *et al.* (1969) defined the varnish material as amorphous by electron microprobe. Desert varnish sampled from the Dry Valleys, Antarctica has been studied by GLASBY *et al.* (1981) and JOHNSTON *et al.* (1984). They showed that the varnish is a dark brown coating rich in Fe and that may be originated from chemical weathering, *i.e.*, leaching of elements from the inner region of substrate rock. JOHNSTON and CARDILE (1984) have also conducted the chemical analysis of desert varnish sampled from the Dry Valleys and concluded that desert varnish layers were thin coatings of a poorly-ordered hydrated ferric oxide polymer.

Chemical texture of desert varnish was investigeted by the present authors, using the electron probe micro-analyzer. Cobble size pieces of granitic gneiss sampled from the central part of South Balchenfjella were selected for the analysis of varnish. Chemical analysis clearly defined the varnish to be a film composed of crystalline jarosite, $KFe_3(SO_4)_2(OH)_6$, mixed with amorphous silica. A coat of jarosite 1 to 10 μm thick covers directly on the fresh rock surface, but a narrow opening sometimes exists between the varnish layer and the rock surface. Further analysis proved the interesting fact that crystalline jarosite mixed with amorphous silica was also found in very narrow cracks within the inner fresh region of the gneiss. It is considered that these cracks were originally gaps between individual minerals or were formed along cleavages or foliations. They look like veins of jarosite matter. These veins often continue to the varnish coating on the rock surface. This fact suggests that a solution containing K^+, Fe^{3+}, and SO_4^{2-} ions with amorphous silica, SiO_2, ascends through these cracks. Microphotographs of desert varnish are shown in Plates 6.A to 6.D and an idealized mechanism of desert varnish formation is drawn in Fig. 4.

Chemical characteristics and a mechanism of varnish formation may safely be said as follows. Desert varnish is a film composed of crystalline jarosite mixed with amorphous silica and is formed by evaporation of solutions which are supplied from the underlying ground by capirally action. Sulfuric acid is important to dissolve the

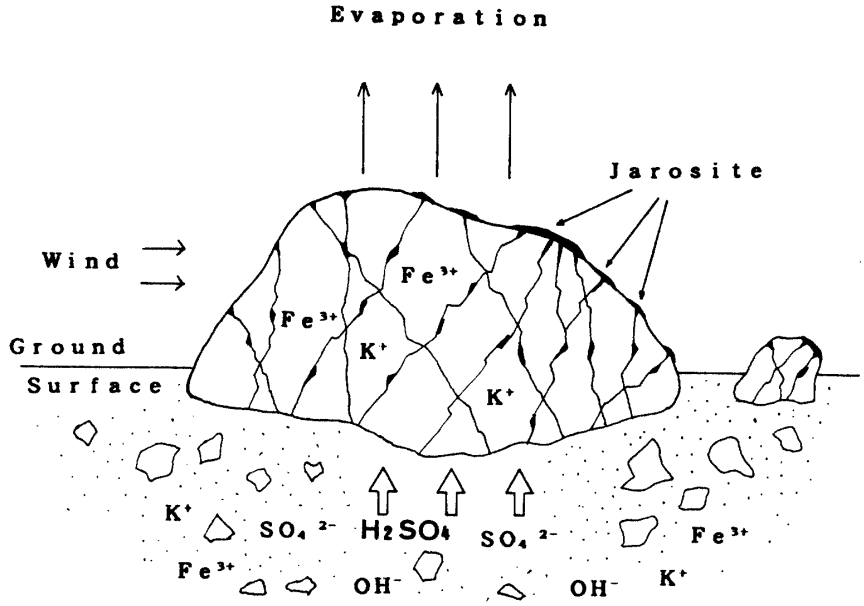

Fig. 4. Idealized mechanism of the desert varnish formation. Solution of sulfuric acid supplied from the underlying ground ascends through cracks within a rock and forms the varnish coat on the surface by evaporation.

minerals under the ground and sometimes in the inner region of a rock. It is possible that jarosite works to expand the cracks wider during its crystallization.

6. Summary

The characteristics of glacial landforms and weathering phenomena in the Balchenfjella region are summarized as follows:

(1) The Balchenfjella region lies at a rather lower elevation than the other parts of the Sør Rondane Mountains and had entirely been covered with the former ice sheet flowing from south to north. Alpine features poorly develop in this region.

(2) Judging from the degree of weathering around the mountain peaks, the deglaciation occurred at first in the northern region, Austharmaren-Vesthjelmen area. Succeedingly, the southern part of South Balchenfjella and the mountain tops in the Bulken-Hesteskoen area became free from ice. The North Balchenfjella area emerged in the latest stage of deglaciation.

(3) A remarkable ice step due to damming of ice flow by the mountain's threshold is observed on the ice sheet behind South Balchenfjella. It has probably been formed since rather an earlier stage of deglaciation. The stage of deglaciation around the areas from Bulken to South Balchenfjella was strongly controlled by this ice step.

(4) Shattering and granular disintegration are most predominant among weathering features in this region. Salt aggregations, mostly composed of gypsum, are often found in this region. Beautifully crystallized gypsum, 30 cm in longest is formed in a lower part of North Balchenfjella.

(5) Desert varnish was clearly defined to be a film composed of crystalline jarosite mixed with amorphous silica. The varnish coat is formed by a solution of

sulfuric acid provided from the underlying ground. Capirally action is effective for this solution to ascend through cracks within a rock.

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